Laser Shock Processing:

An Advanced Technique for Improving the Surface and Mechanical Properties of Metallic Alloys

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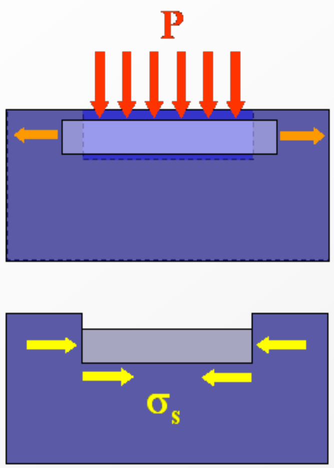
OUTLINE:

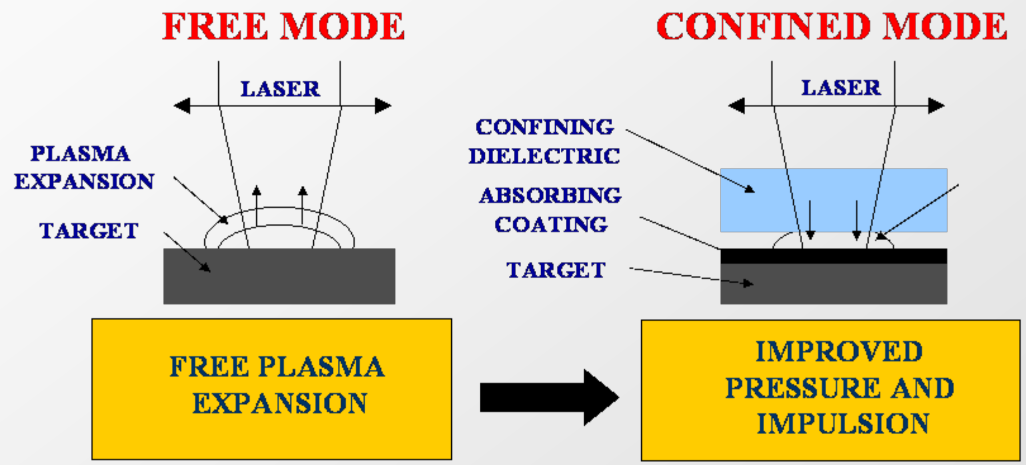
- Introduction
- Summary on the Physical Basis of LSP Treatments
- Experimental LSP Setup at CLUPM
- Experimental results
  - a) Surface Properties enhancement of Al and Ti alloys
  - b) Fatigue Life enhancement of AISI 316L specimens
- Discussion and Outlook

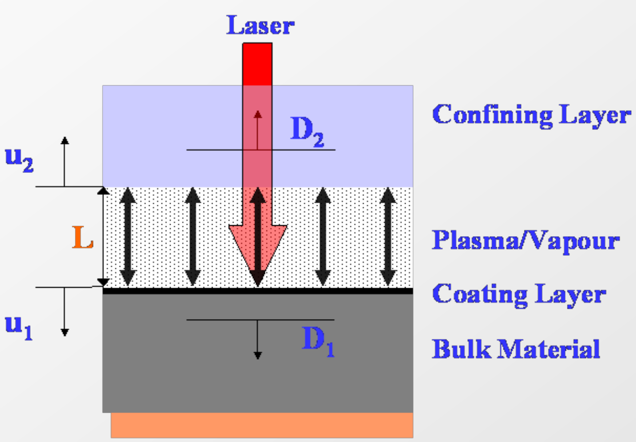
INTRODUCTION

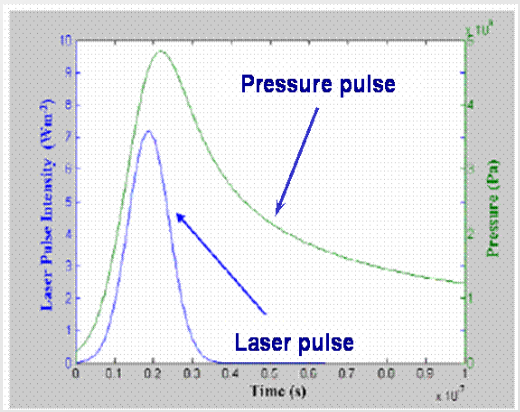
- Profiting by the increasing availability of high intensity laser sources, laser shock processing (LSP) is being consolidating as an effective technology for the improvement of surface and mechanical properties of metallic alloys and is being developed as a practical process amenable to production engineering.
- The main acknowledged advantage of the laser shock processing technique consists on its capability of inducing a relatively deep compression residual stresses field into metallic alloy pieces allowing an improved mechanical behaviour, explicitly, the life improvement of the treated specimens against wear, crack growth and stress corrosion cracking in direct competence with other established technologies as, i.e. shot peening.
- After a description of the theoretical/computational and experimental methods developed by the authors for the predictive assessment and experimental implementation of LSP treatments, experimental results on the residual stress profiles and associated surface properties modification successfully reached in typical materials under different LSP irradiation conditions are presented.
- The highly beneficial effect of LSP treatments has been demonstrated in the evaluation of surface properties and extension of life of test specimens of different key materials (AISI 316L, Al2024-T351, Ti6Al4V).

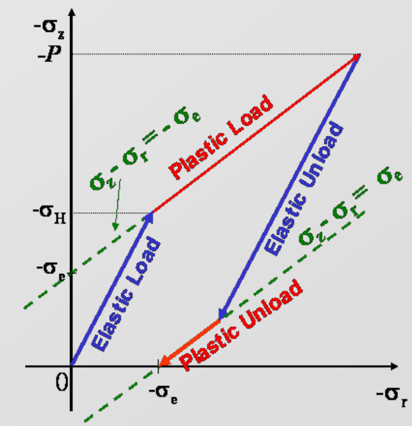
REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)



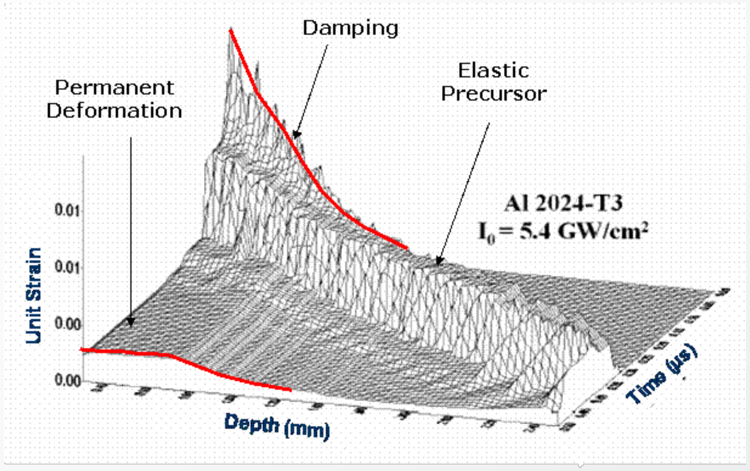


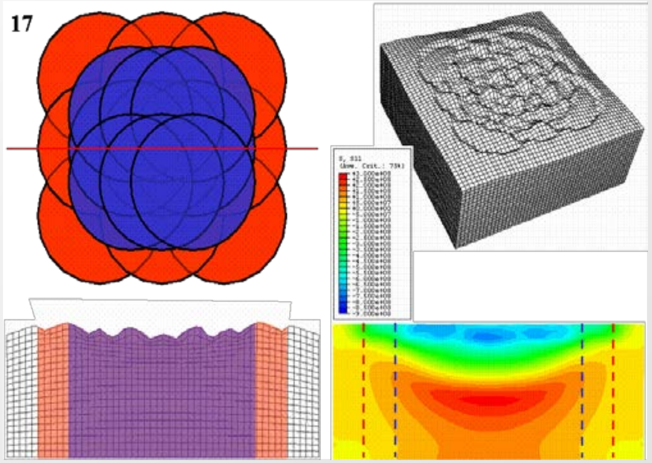


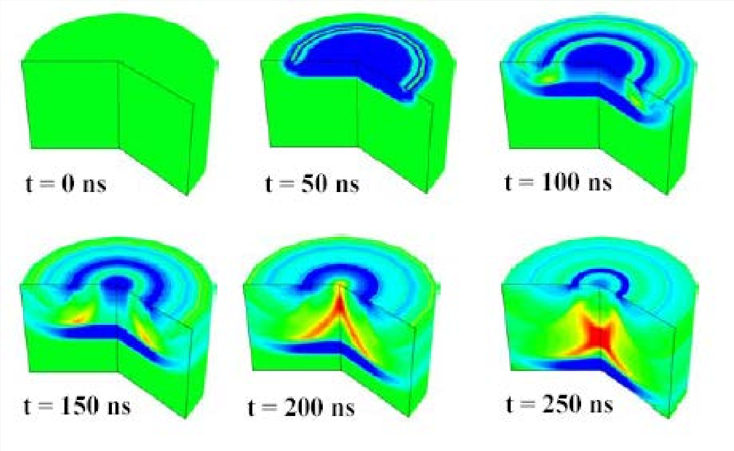


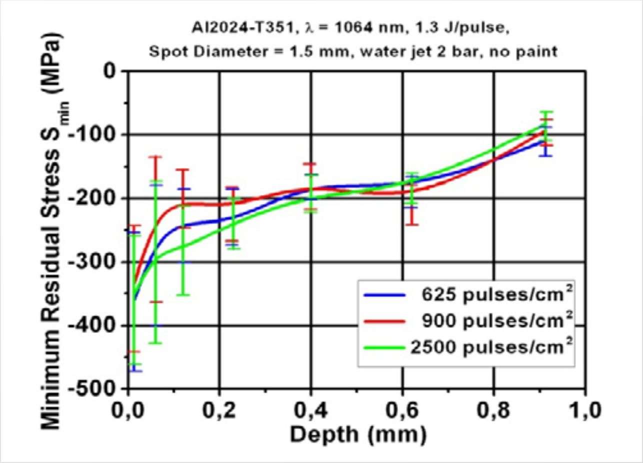


REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)

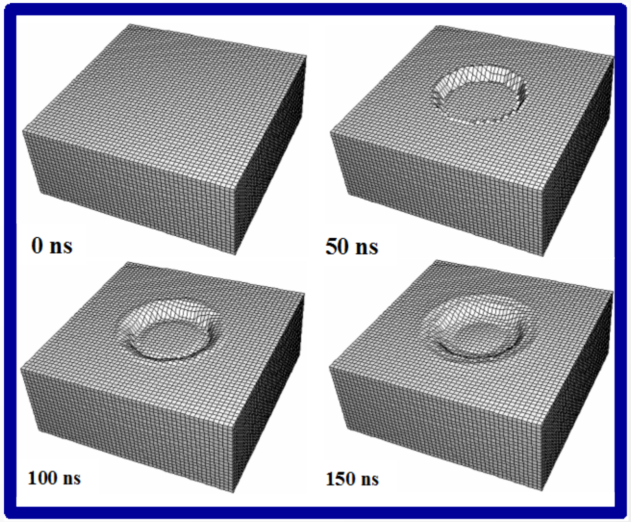


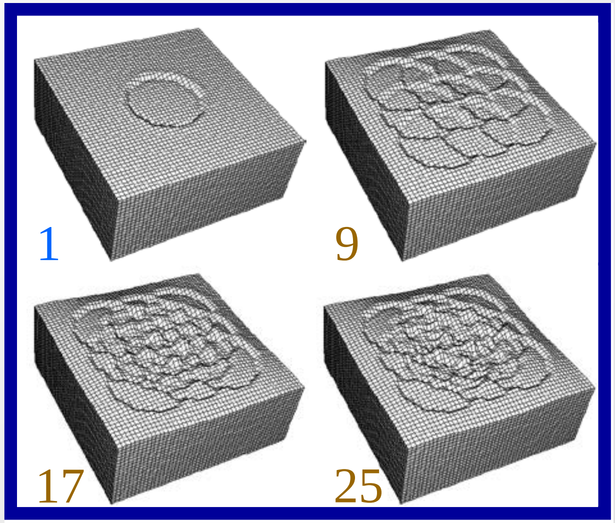


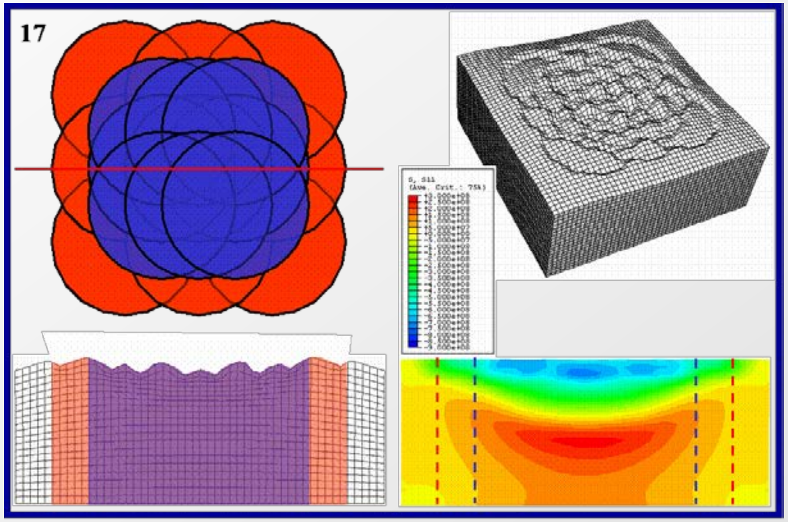


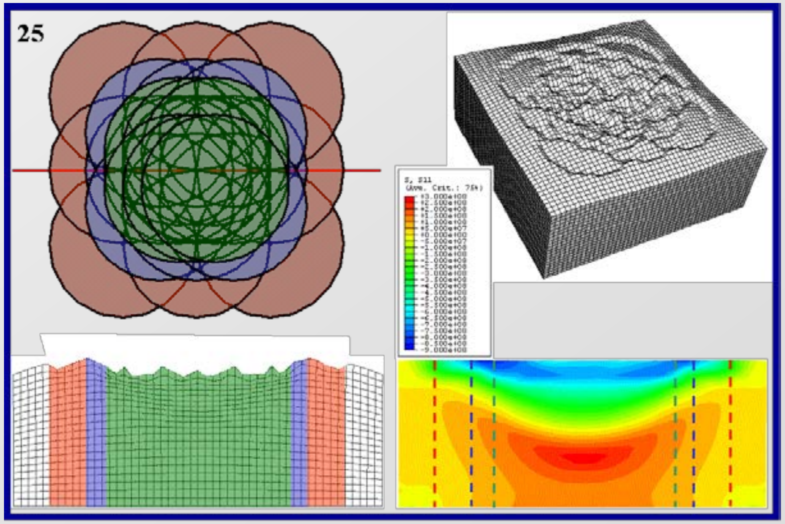


SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP

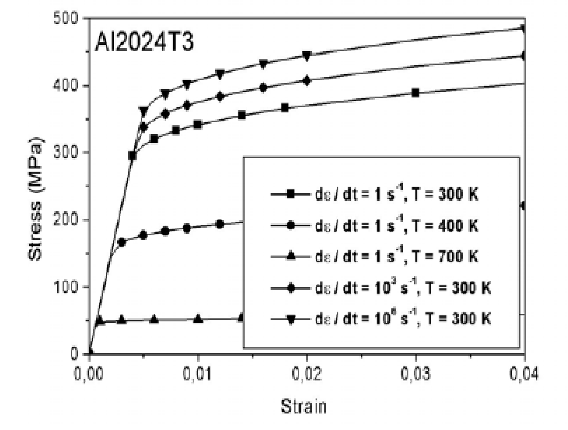


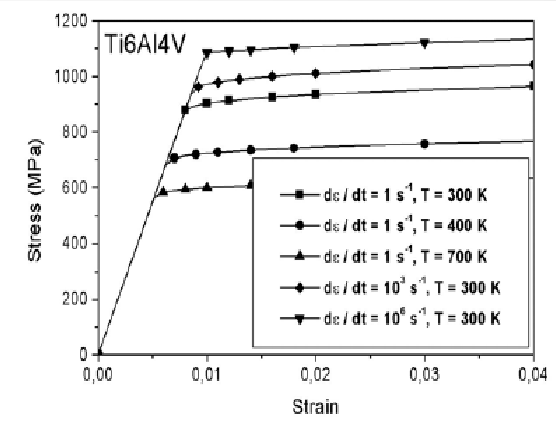


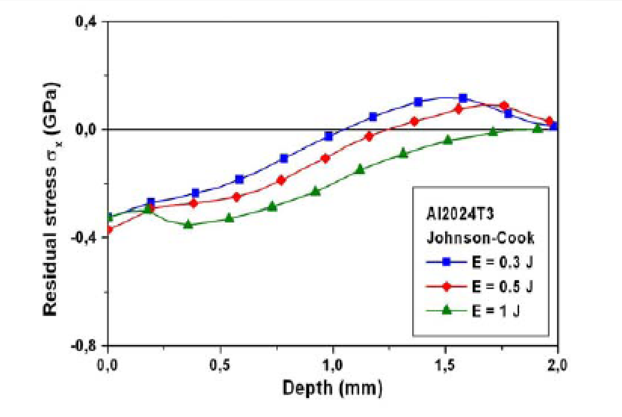


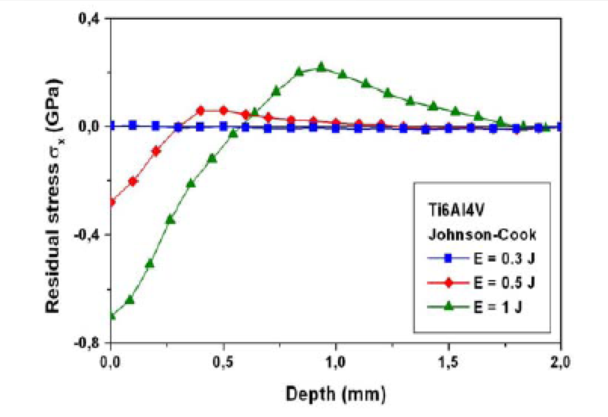


SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP









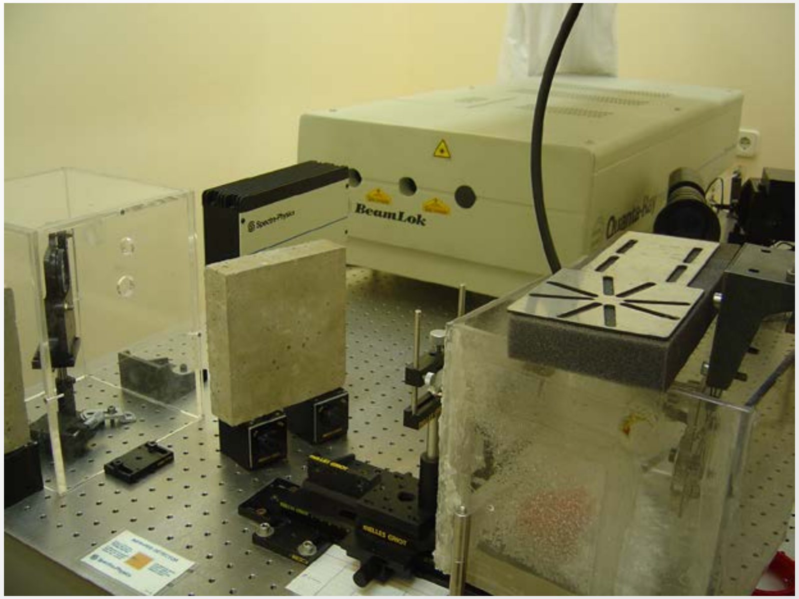
Ocaña, J.L. et al.: "Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser-shock-processed metallic alloys". Proc. SPIE 5448, 642-653 (2004)

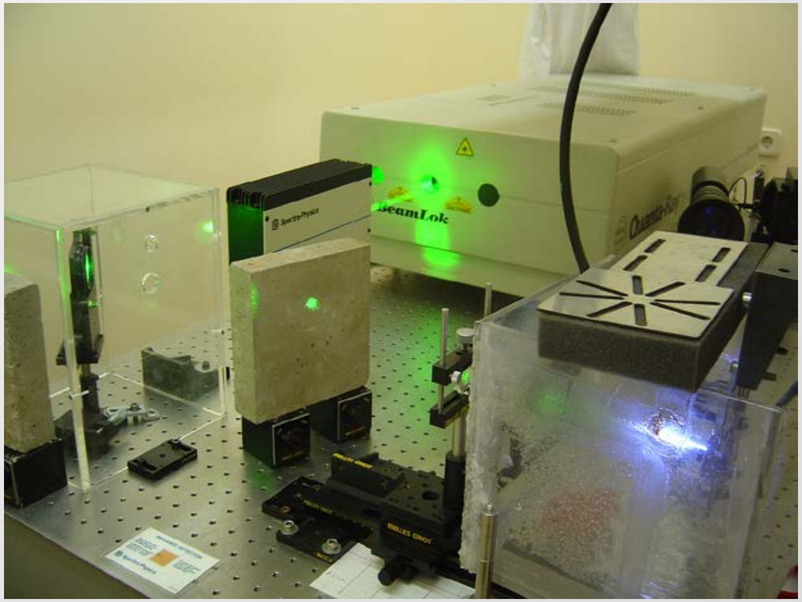
PROCESS EXPERIMENTAL SETUP

Q-SWITCHED Nd:YAG LASER

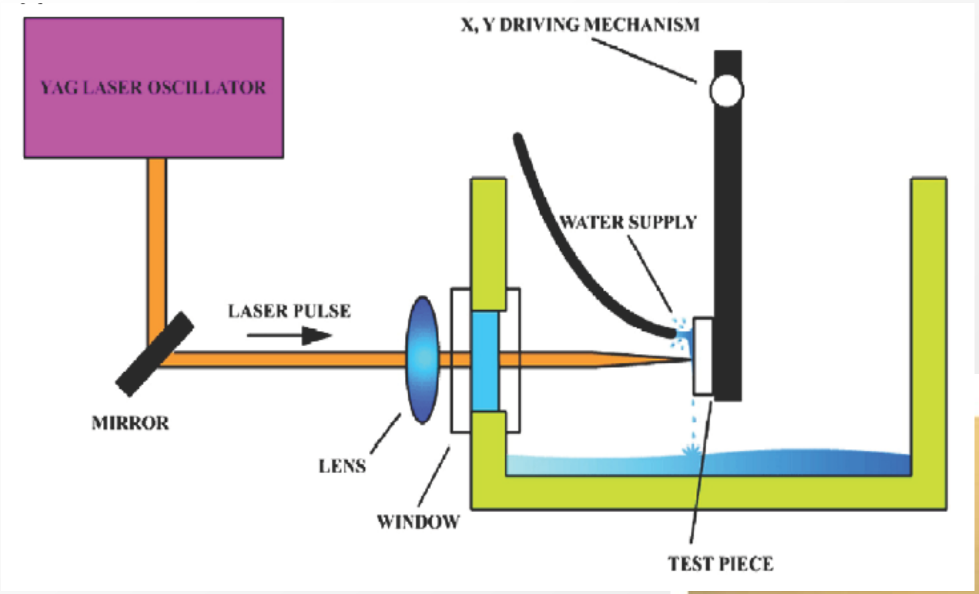
$$\begin{cases} \lambda = 1064\,\text{nm};\ E = 2{,}5\ \text{J/pulse} \\ \lambda = 532\,\text{nm};\ \ E = 1{,}4\ \text{J/pulse} \end{cases}$$

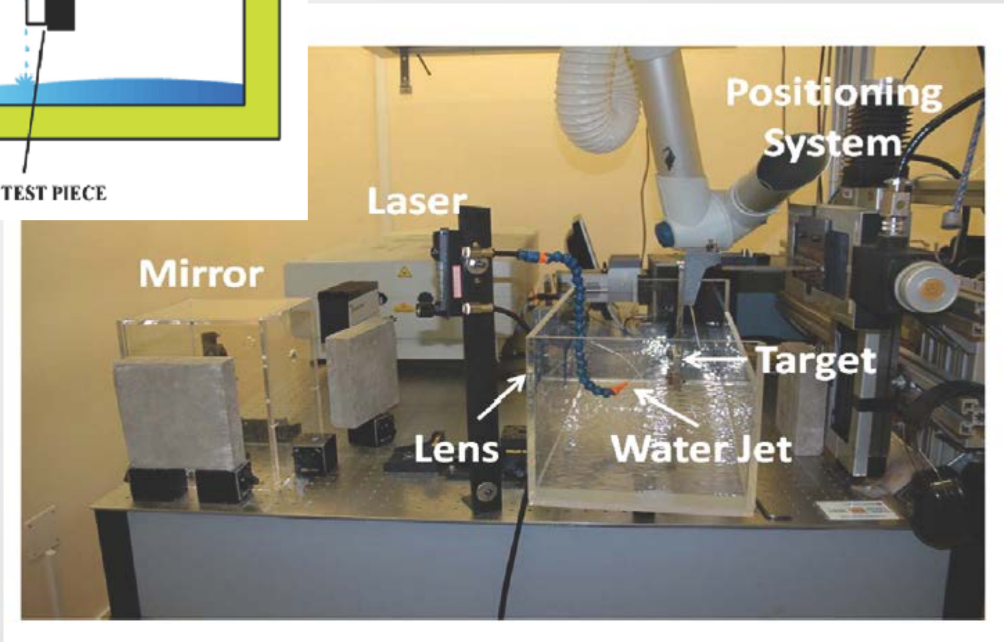
τ = 10 ns; f = 10 Hz





PROCESS EXPERIMENTAL SETUP





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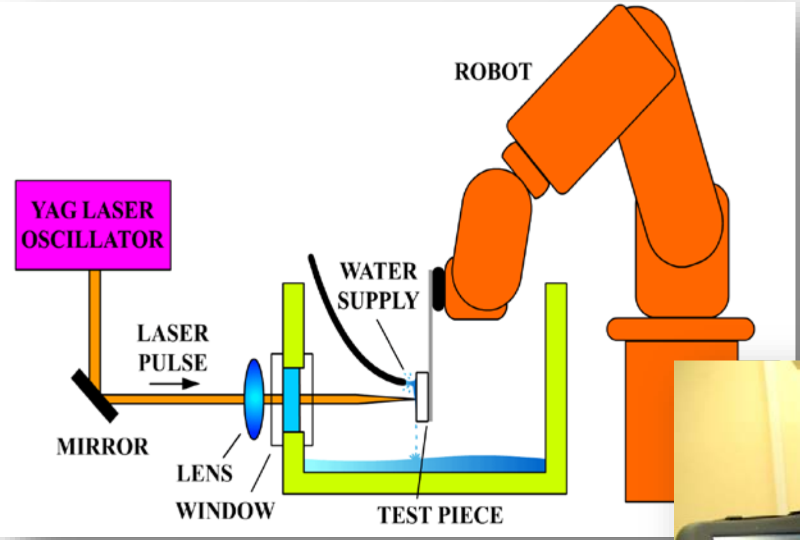
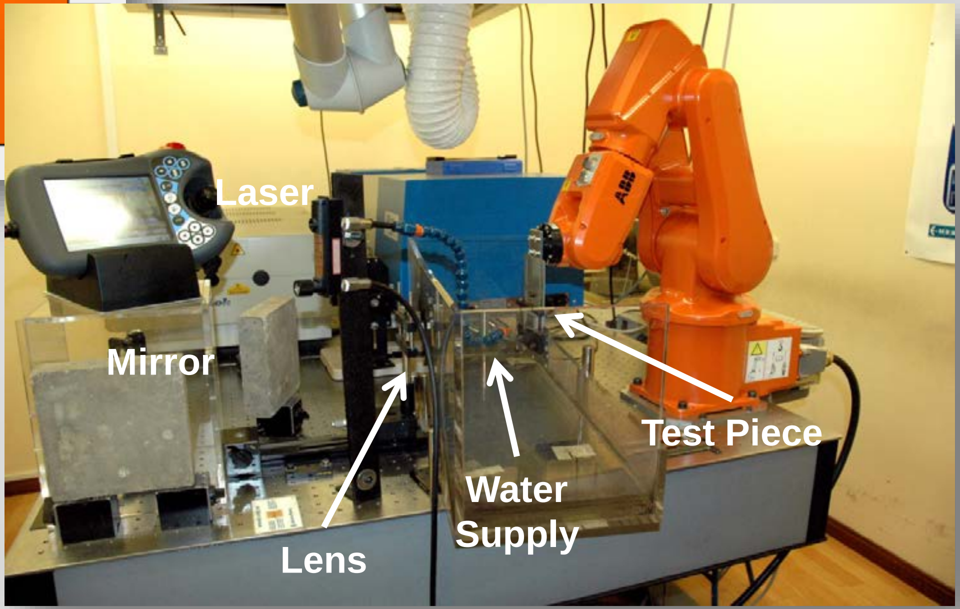
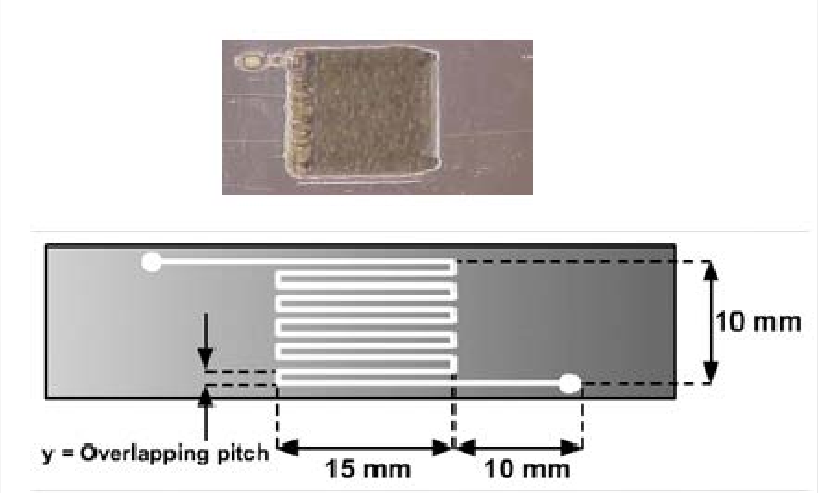




PROCESS EXPERIMENTAL SETUP

PROCESS EXPERIMENTAL SETUP

EXPERIMENTAL PROCEDURE

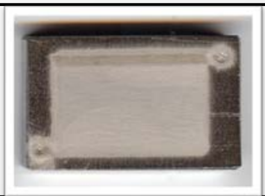
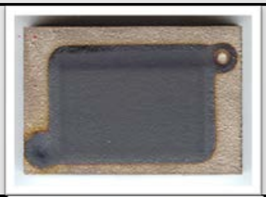


$$\text{Equivalent Overlapping Density} \equiv \mathrm{EOD} = \frac{\mathrm{N^o\ of\ pulses}}{\mathrm{Total\ treated\ surface}} = \frac{\dfrac{x}{\Delta x}\,\dfrac{y}{\Delta y}}{\Delta s} = \frac{\dfrac{x}{d}\,\dfrac{y}{d}}{xy} = \frac{1}{d^2}$$

$$\text{Equivalent Energy Density} \equiv \mathrm{EED} = \frac{\mathrm{N^o\ of\ pulses} \cdot \mathrm{Pulse\ Energy}}{\mathrm{Total\ treated\ surface}} = \frac{\dfrac{x}{\Delta x}\,\dfrac{y}{\Delta y}}{\Delta s} E = \frac{\dfrac{x}{d}\,\dfrac{y}{d}}{xy} E = \frac{E}{d^2}$$

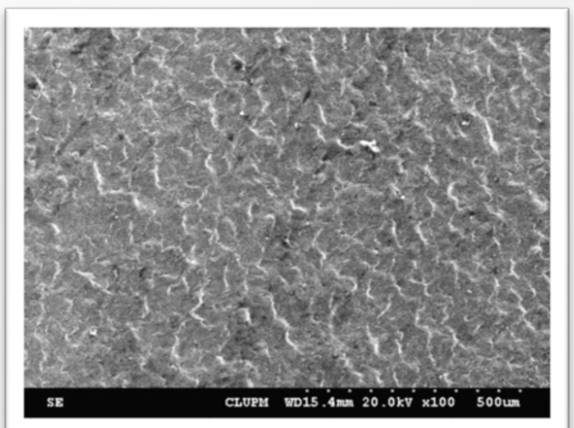
$$\text{Equivalent local overlapping factor} \equiv \mathrm{ELOF} = \frac{\mathrm{N^o\ of\ pulses} \cdot \mathrm{Pulse\ Area}}{\mathrm{Total\ treated\ surface}} = \frac{\dfrac{\pi}{4}\phi^2}{d^2} = \frac{\pi}{4}\left(\frac{\phi}{d}\right)^2$$

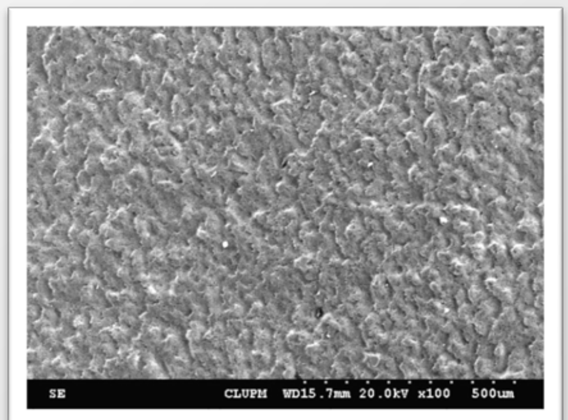
Reported Analysis

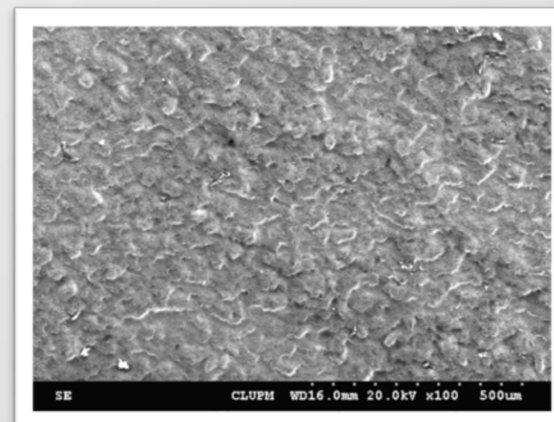
	Al2024-T351 **30x20x8 mm^3**	**Ti6Al4V** **30x20x10 mm^3**
900 pulses/cm^2		
1600 pulses/cm^2		
2500 pulses/cm^2		
5000 pulses/cm^2		

EXPERIMENTAL RESULTS

Surface Roughness (Microscopy): Al2024-T351



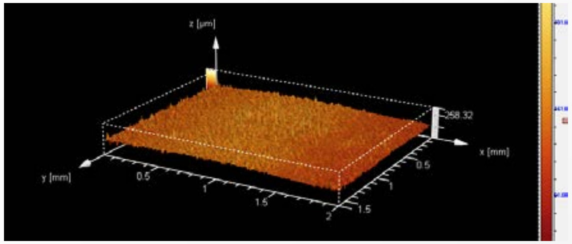


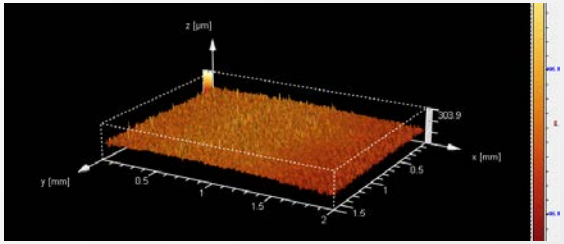


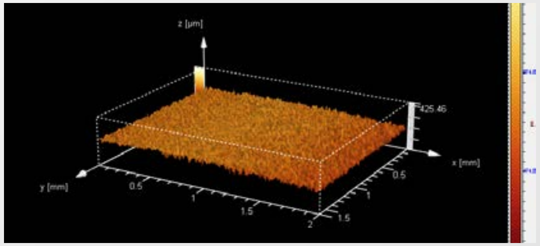
900 pulses/cm^2 | **1600 pulses/cm^2** | **2500 pulses/cm^2**

EXPERIMENTAL RESULTS

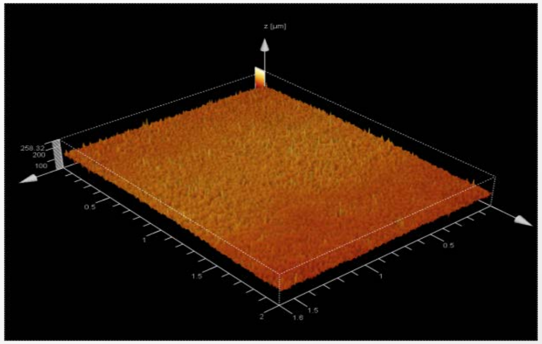
Surface Roughness (Topographic Confocal microscopy): Al2024-T351

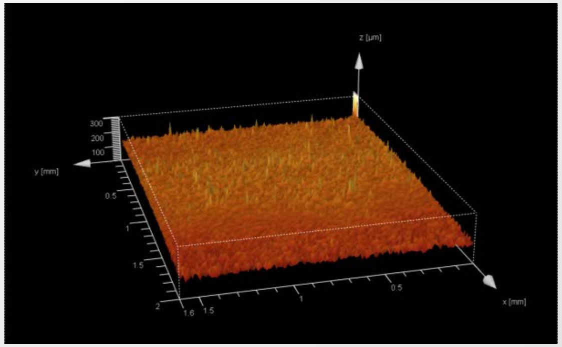


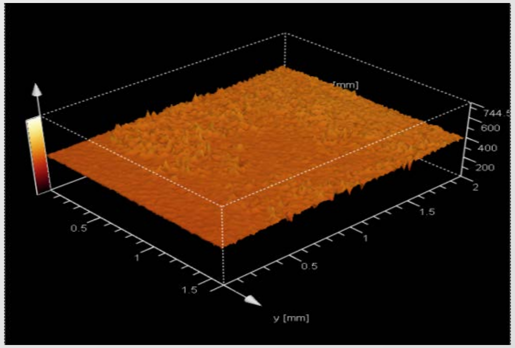




900 pulses/cm^2 | 1600 pulses/cm^2 | 2500 pulses/cm^2



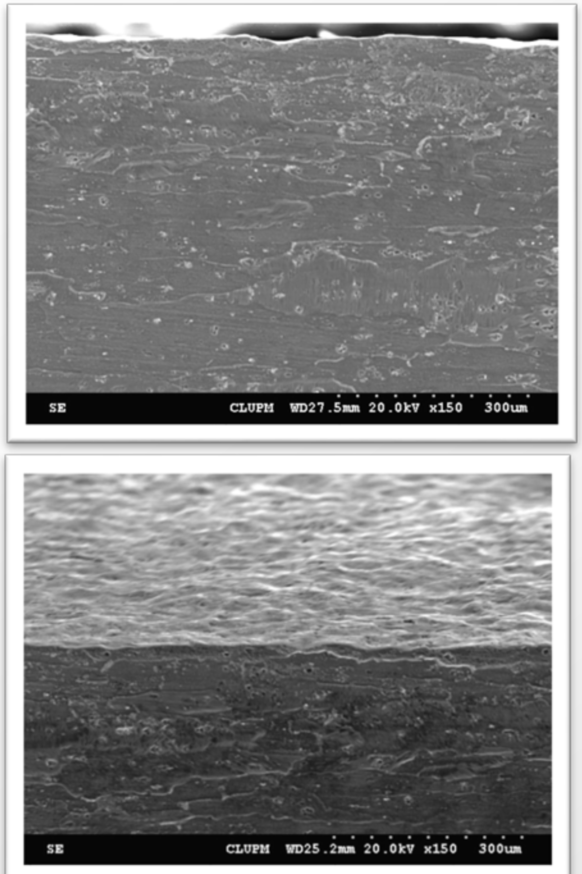




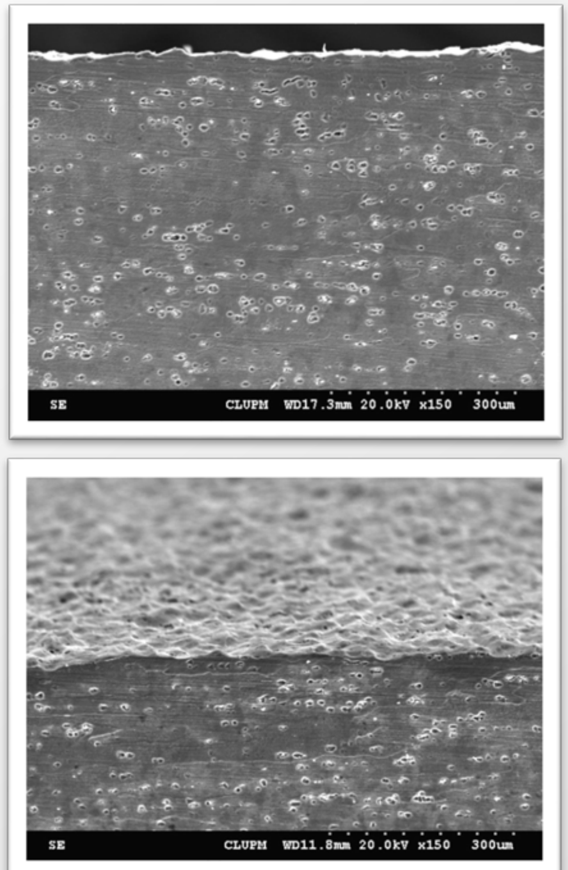
	No treatment	900 pulses/cm^2	1600 pulses/cm^2	2500 pulses/cm^2
Pa (μm)	7.96	5.23	4.82	4.96
$\langle \Delta z \rangle$	----	10.30	20.00	26.82

EXPERIMENTAL RESULTS

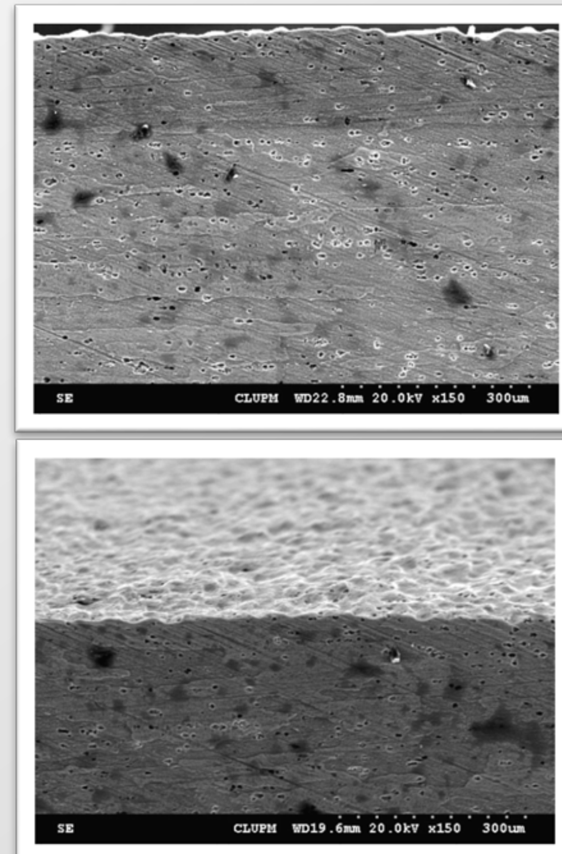
Microscopic material compactation: Al2024-T351



900 pulses/cm^2



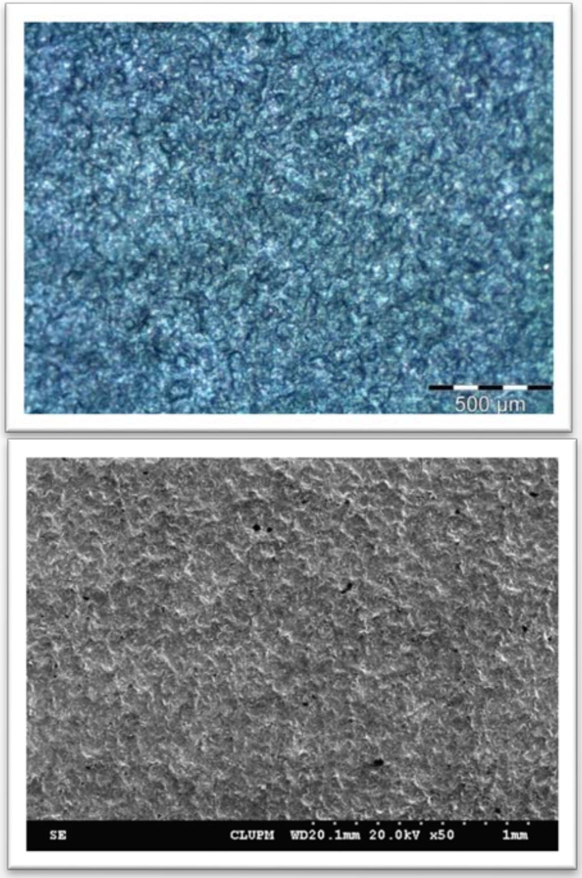
1600 pulses/cm^2



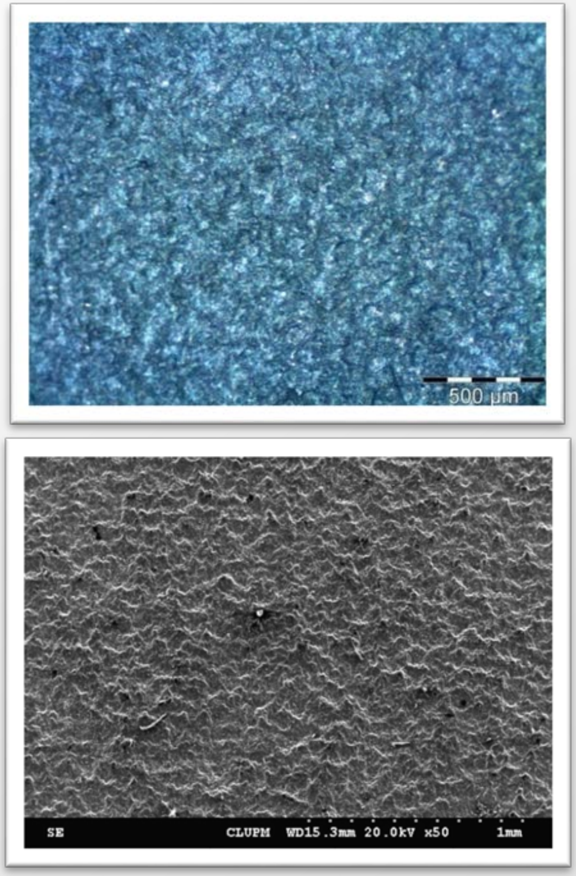
2500 pulses/cm^2

EXPERIMENTAL RESULTS

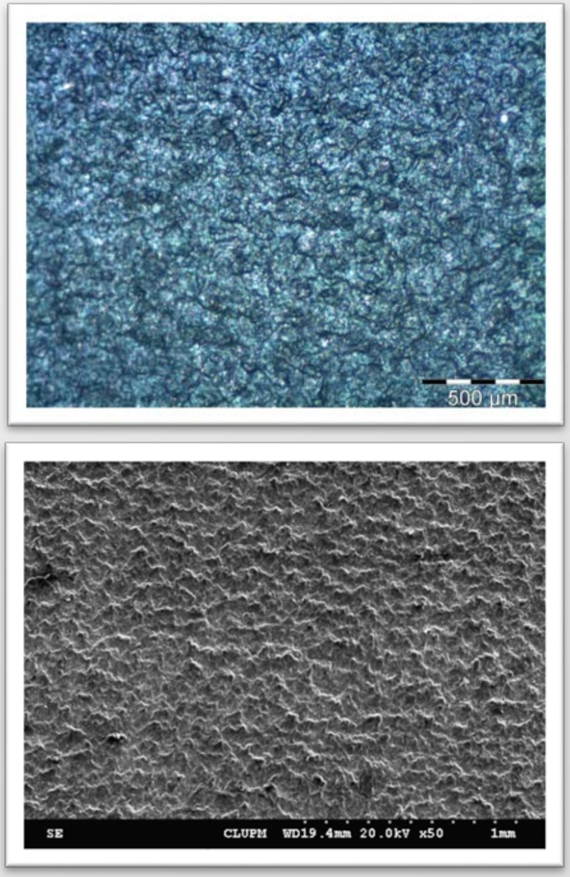
Surface Roughness (Microscopy): Ti6Al4V



900 pulses/cm^2



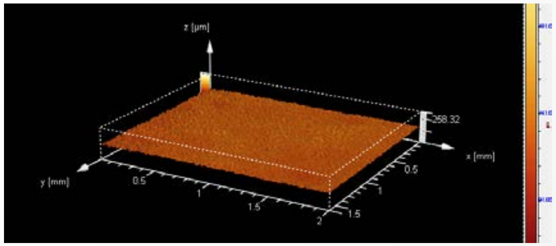
2500 pulses/cm^2

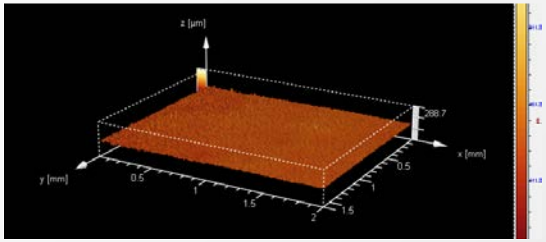


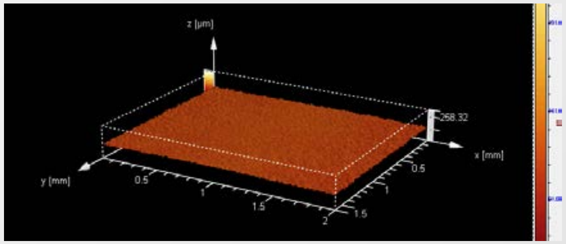
5000 pulses/cm^2

EXPERIMENTAL RESULTS

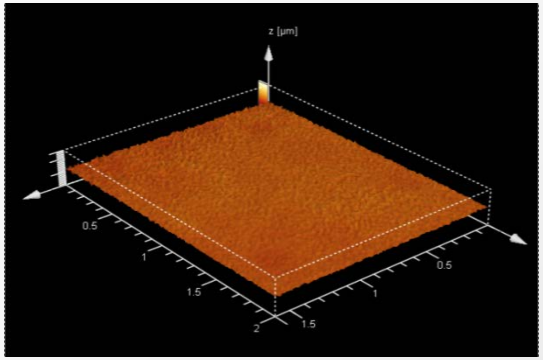
Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

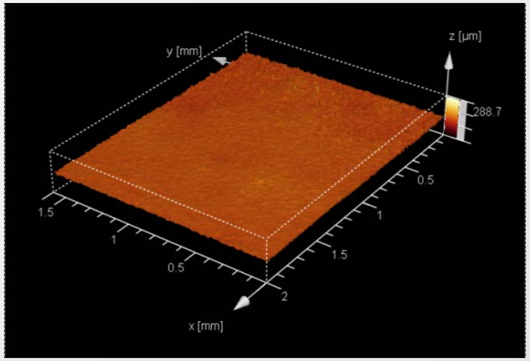


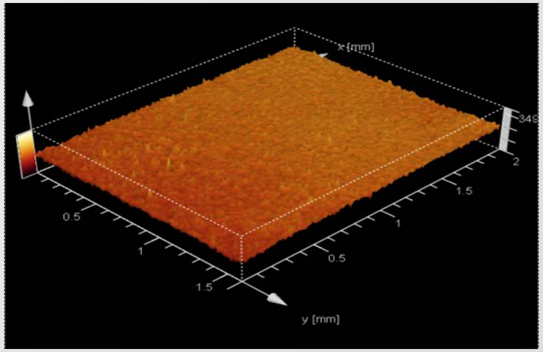




900 pulses/cm^2 | **2500 pulses/cm^2** | **5000 pulses/cm^2**







	No treatment	900 pulses/cm^2	1600 pulses/cm^2	2500 pulses/cm^2
Pa (µm)	9.98	3.62	3.87	3.87
<Δz>	----	2.81	7.40	5.80

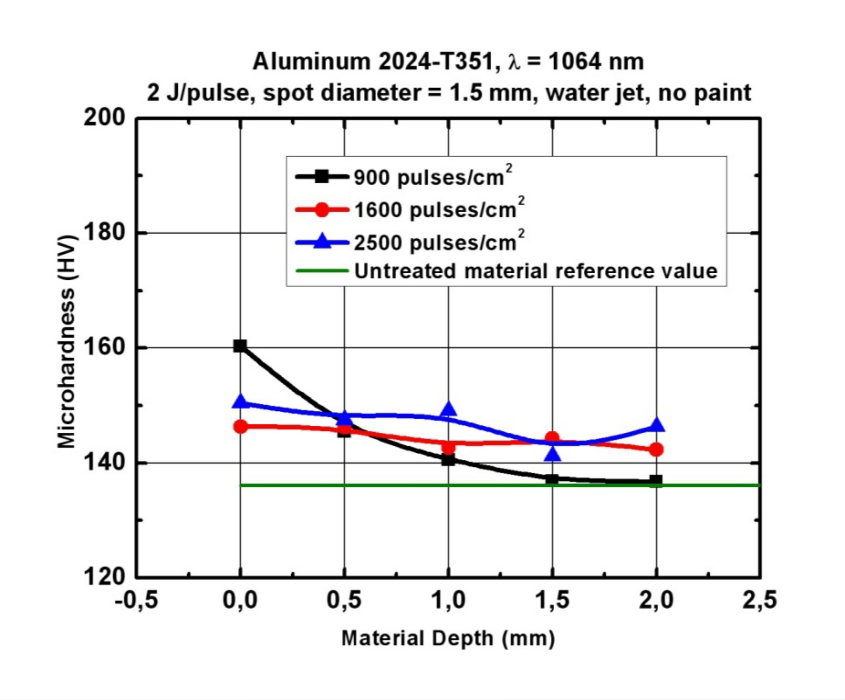
EXPERIMENTAL RESULTS

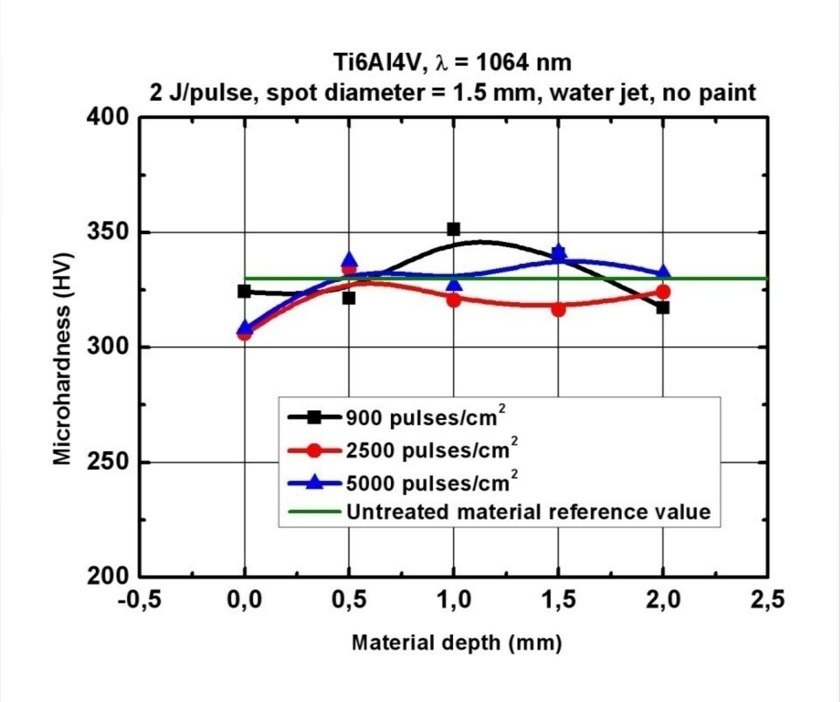
Microscopic material compactation: Ti6Al4V

900 pulses/cm^2 | **2500 pulses/cm^2** | **5000 pulses/cm^2**

EXPERIMENTAL RESULTS

Microhardness (HV)





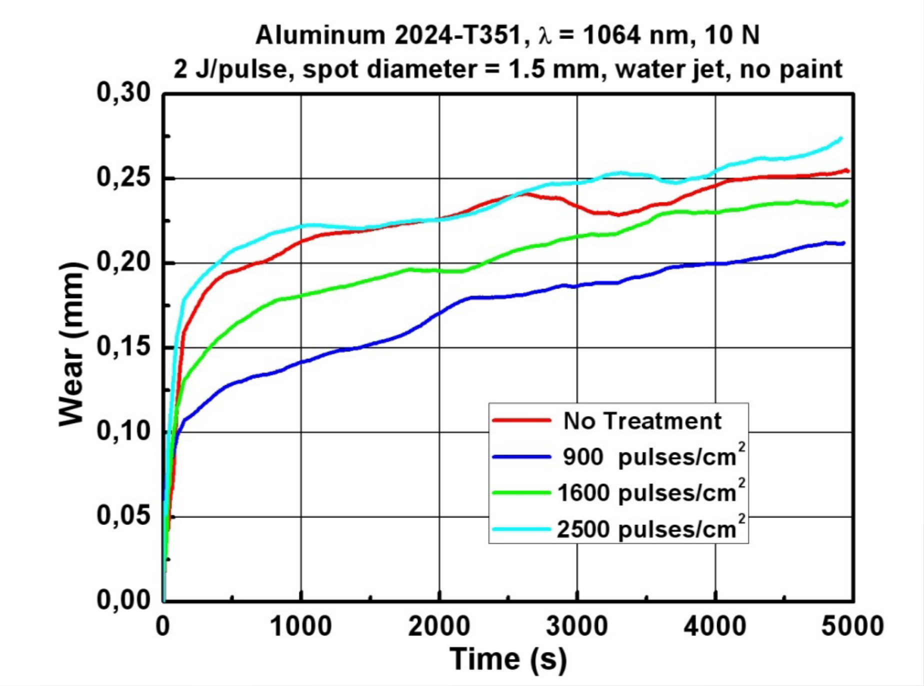
Slight increase in microhardness in Al2024-T351
Higher for higher LSP treatement intensity

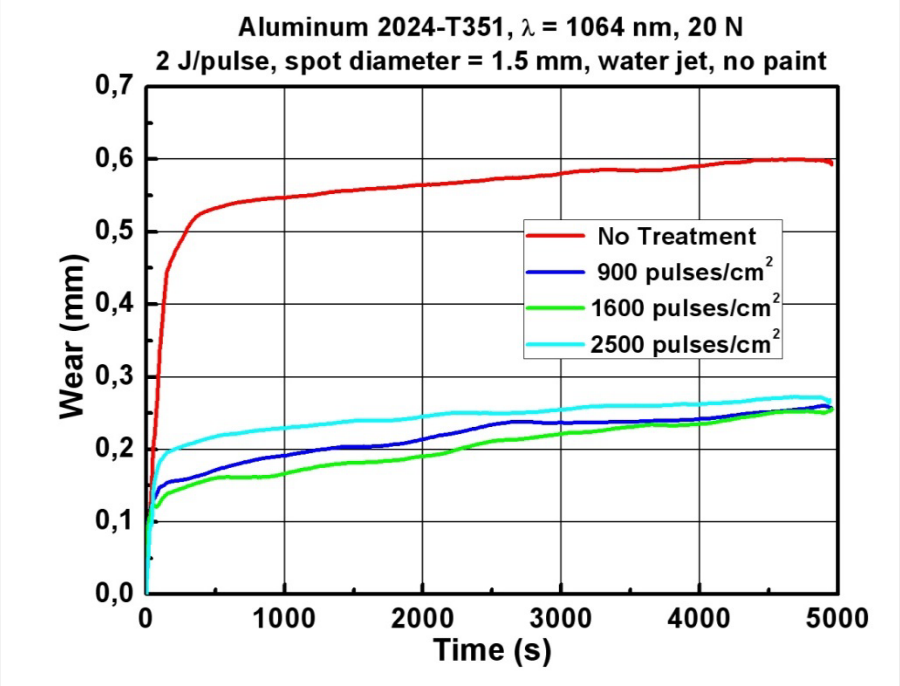
No apparent hardening effect in Ti6Al4V.

EXPERIMENTAL RESULTS

Wear resistance (According to ASTM G99-04)

Al2024-T351





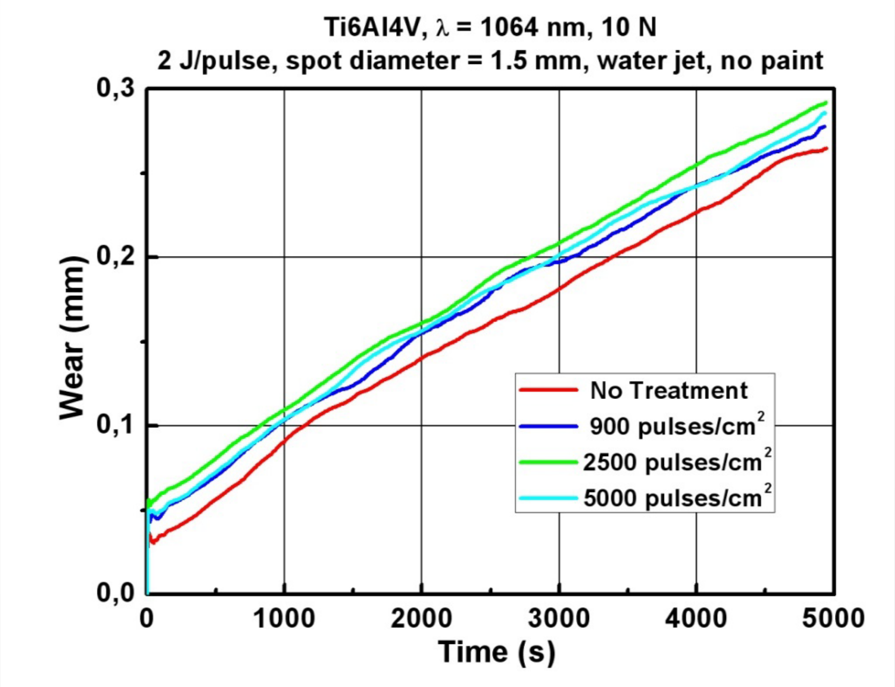
Slight wear improvement in Al2024-T351 at low loads

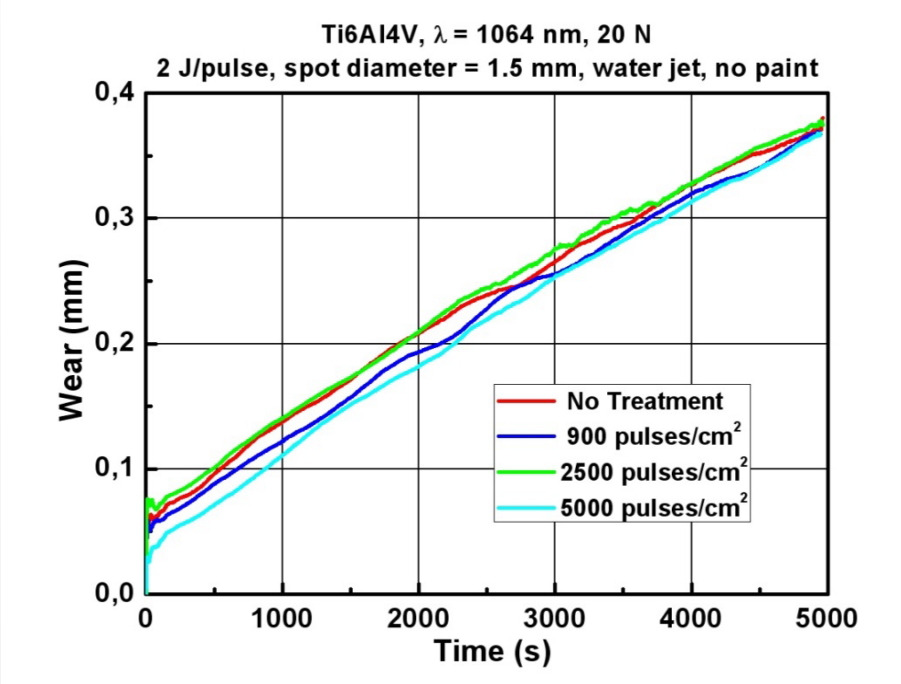
Considerable wear improvement in Al2024-T351 at moderate loads

EXPERIMENTAL RESULTS

Wear resistance (According to ASTM G99-04)

Ti6Al4V

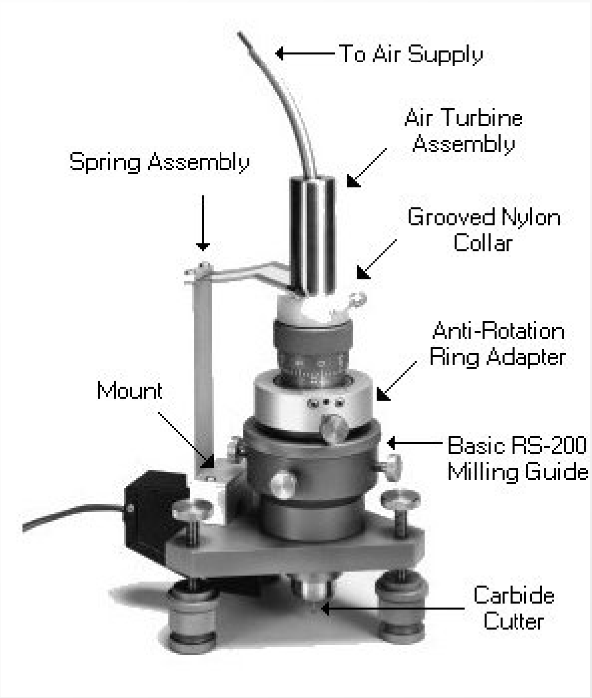


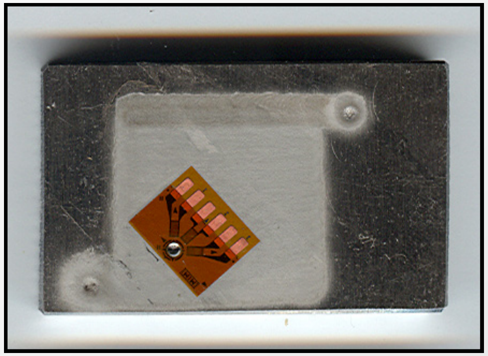


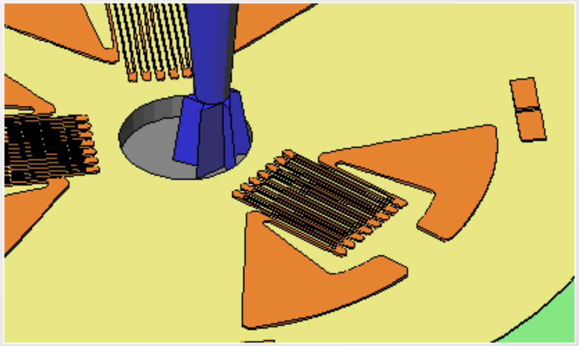
Slight negative wear impact in Ti6Al4V at low loads

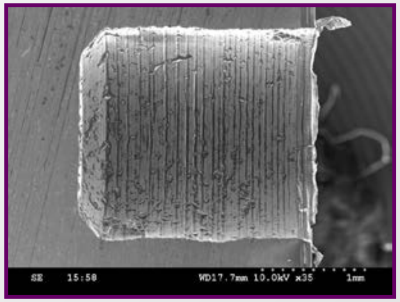
Inappreciable wear improvement in Ti6Al4V at moderate loads

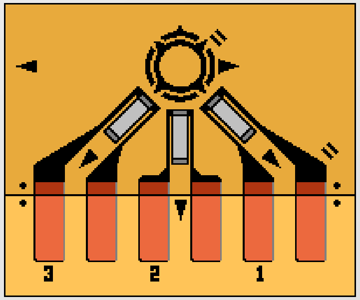
Residual Stresses Measurement Equipment (According to ASTM E837-08)



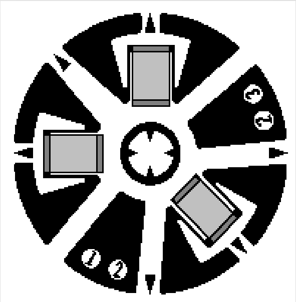








CEA-XX-062UM-120

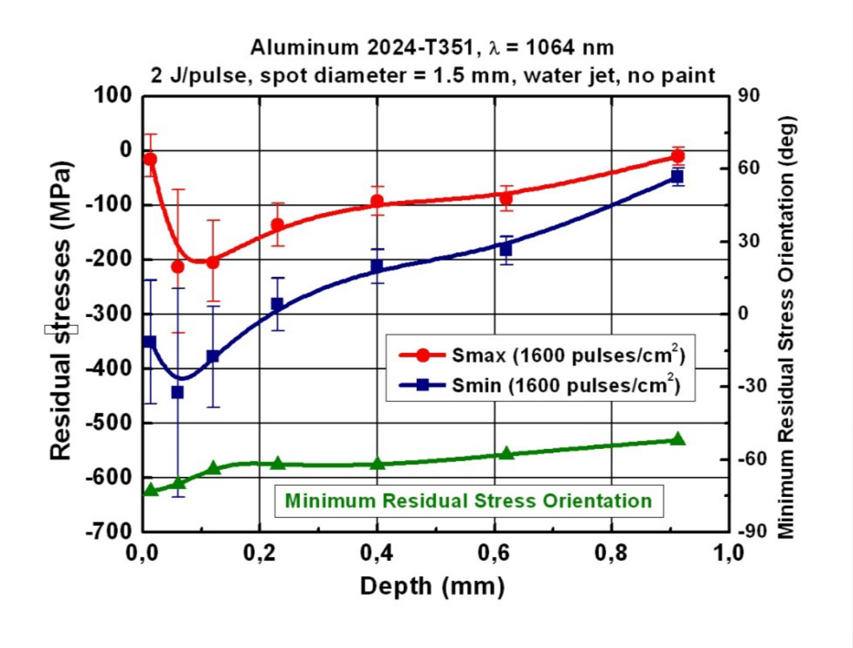


EA-XX-062RE-120

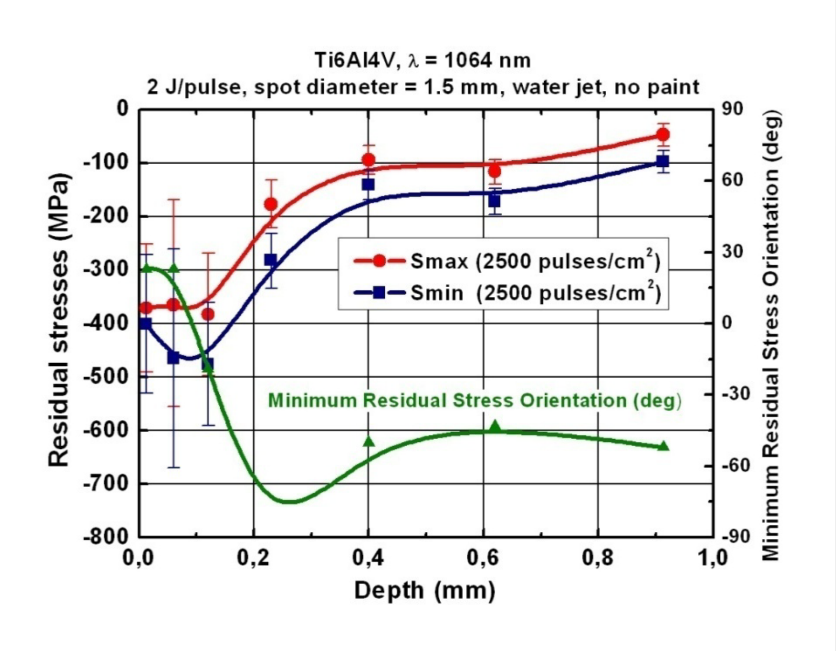
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Al2024-T351



Ti6Al4V



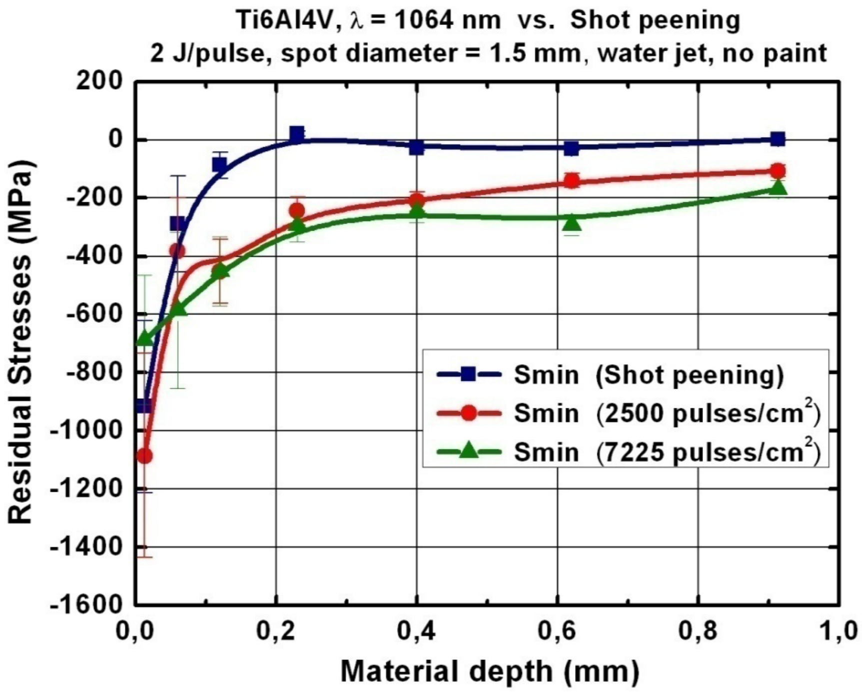
Relatively broad difference between S_{max} and S_{min} in Al2024-T351

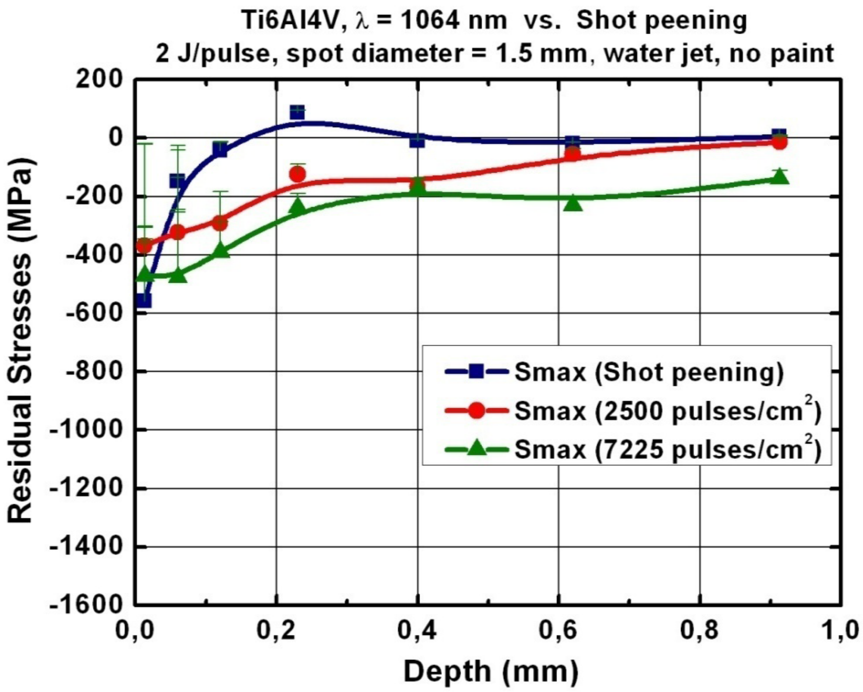
Relatively small difference between S_{max} and S_{min} in Ti6Al4V

EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V: Comparison LSP-Shot Peening



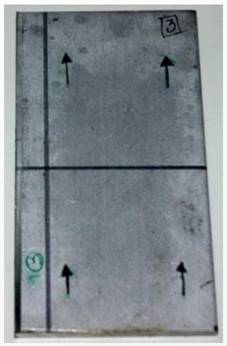


Substantial improvement in Residual Stresses Field in Ti6Al4V vs. to Shot Peening

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities

EXPERIMENTAL RESULTS

Fatigue Life enhancement of AISI 316L specimens



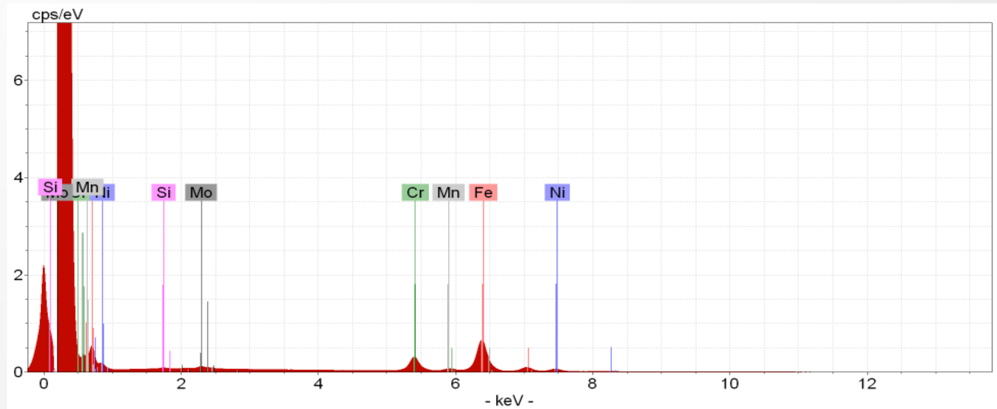


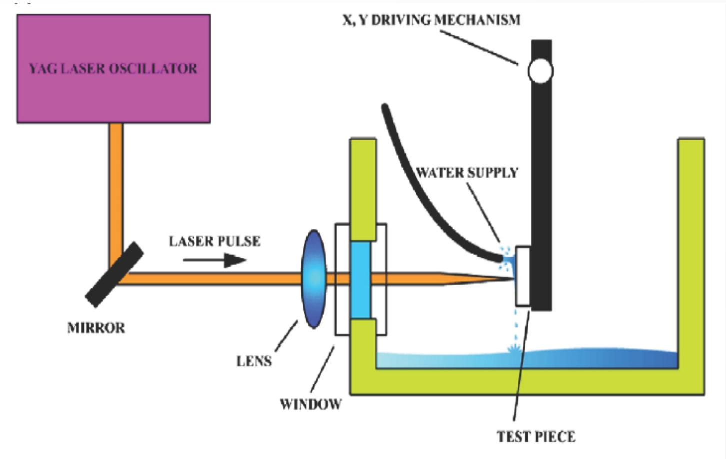
Table 1: Percent Composition of AISI 316L Steel Used in the Reported Experiments

Element	C	Cr	Ni	Mo	Mn	Si	N	P	S	Fe
% wt	0.018	16.815	10.086	2.044	1.294	0.458	0.047	0.032	0.003	Bal.

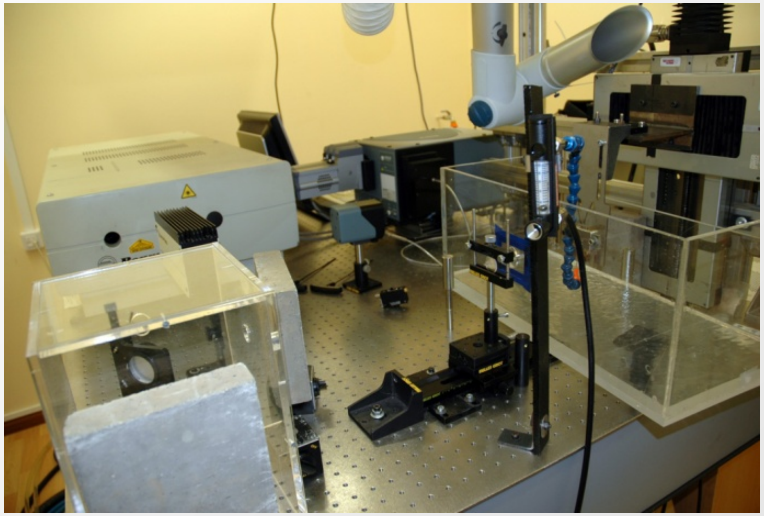
Table 2: Initial Mechanical Properties of AISI 316L Steel Used in the Reported Experiments

Property	Value
Elastic Modulus [GPa]	177.2
Offset Tensile Yield Strength [MPa]	355.4
Ultimate Tensile Strength [MPa]	633.6

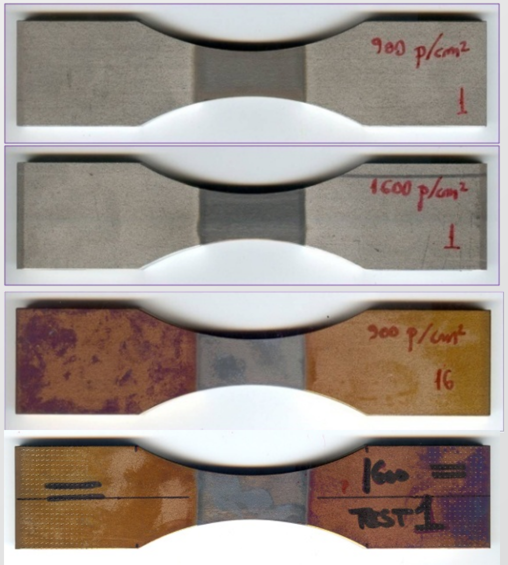
EXPERIMENTAL RESULTS



Process parameters	
Wavelength (nm)	1064
Frecuency (Hz)	10
Energy (J/pulse)	2.0
Pulse width (ns)	~ 9
Spot diameter (mm)	~ 1.5
Overlapping (pulses/cm²)	900
	1600
Confining medium	Water jet
Absorbent coating	No



Experimental setup LSP CLUPM



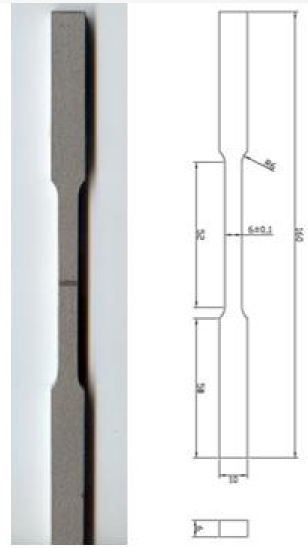
900 pulses/cm²

1600 pulses/cm²

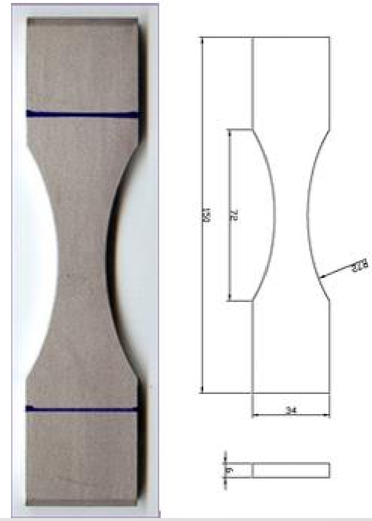
900 pulses/cm² + Heat treat.: 500 ˚C, 8h

1600 pulses/cm² + Heat treat.: 500 ˚C, 8h

EXPERIMENTAL RESULTS



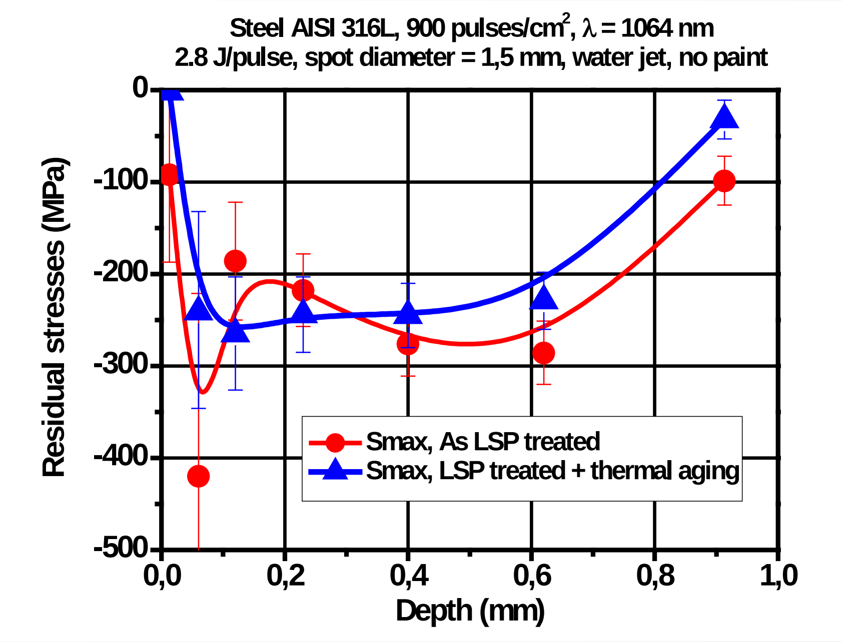
"Sub-size" Tensile Specimen
ASTM E 8M

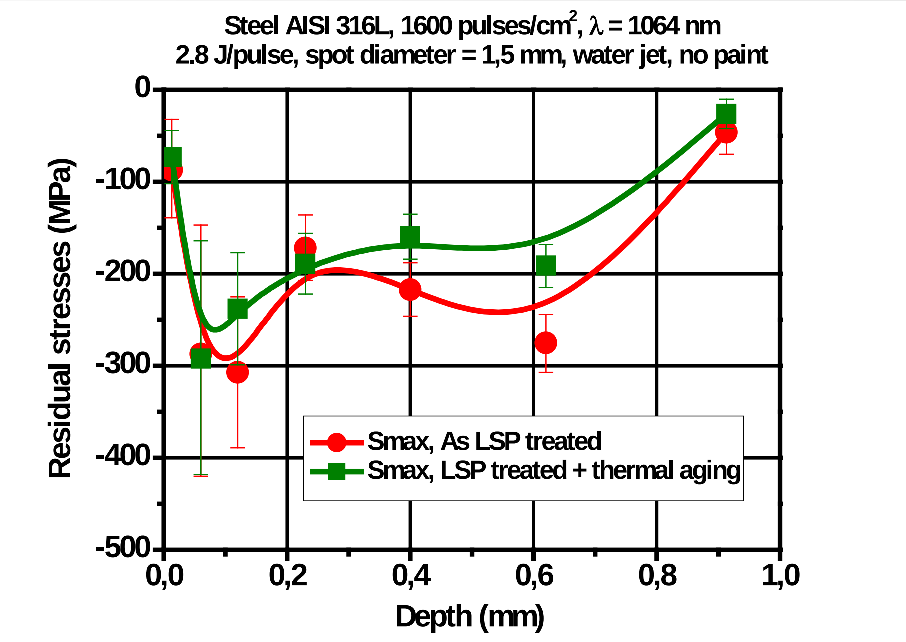


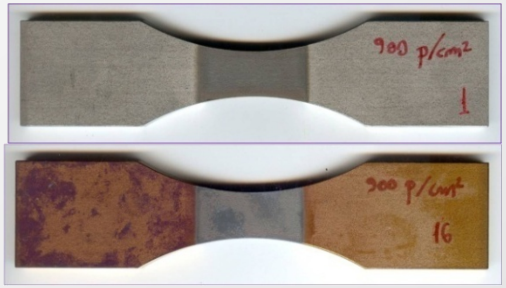
"Bone" Fatigue Specimen
ASTM E 466

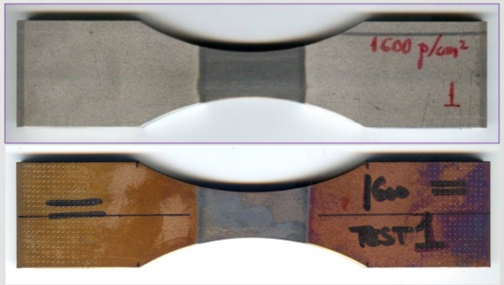
EXPERIMENTAL RESULTS

Residual Stresses:



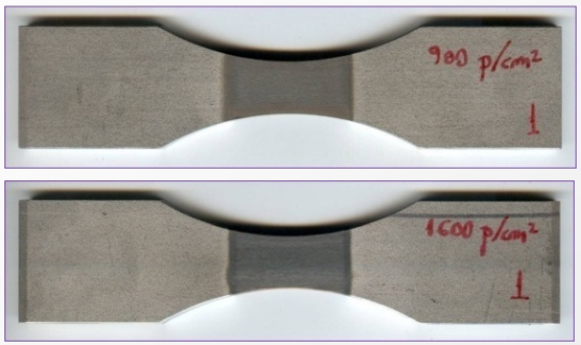


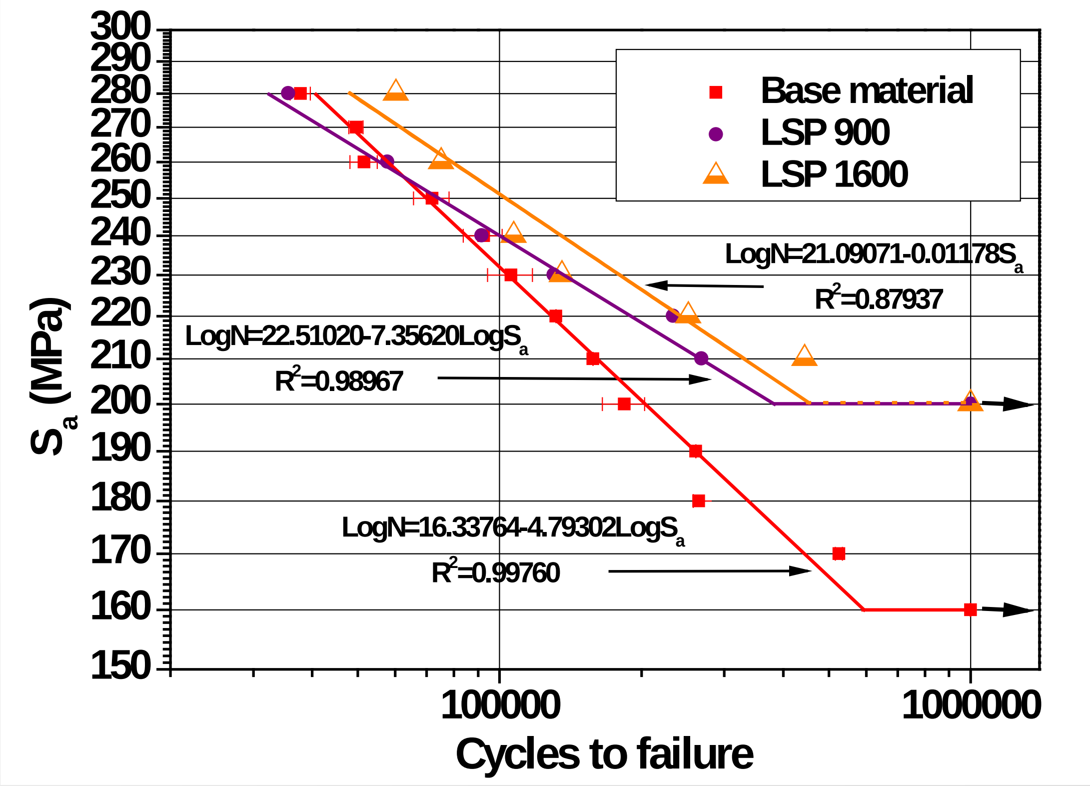




EXPERIMENTAL RESULTS

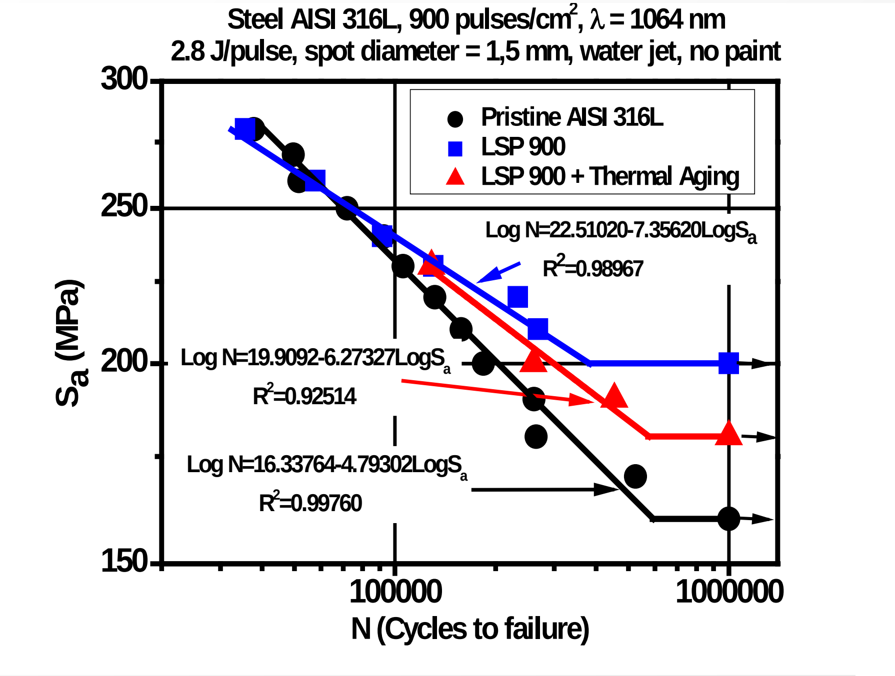
Fatigue Tests:

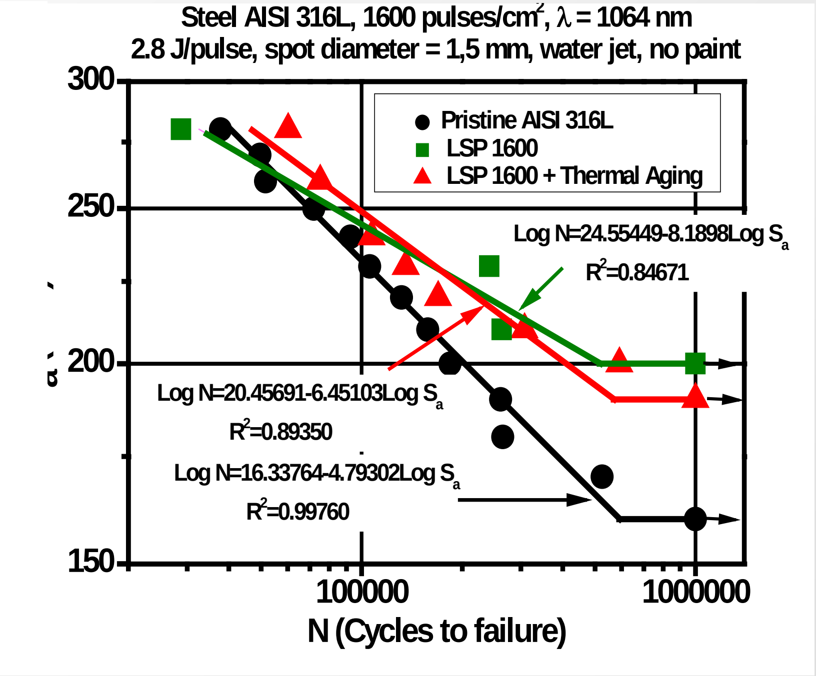


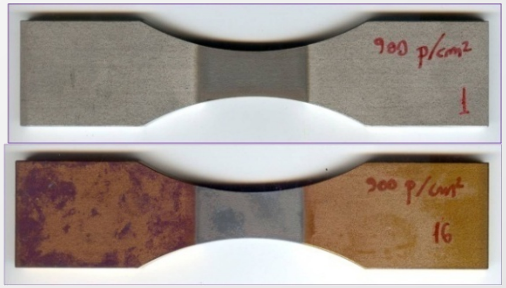


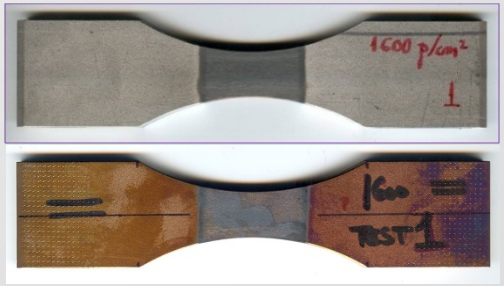
EXPERIMENTAL RESULTS

Fatigue Tests:









DISCUSSION AND OUTLOOK

A typical prospective LSP application to welding technology

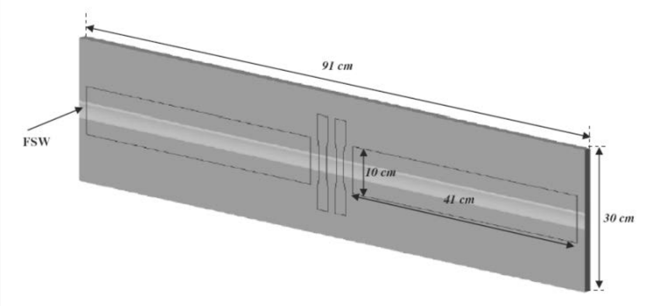


Fig. 2. Dimensions of the FSW plate.

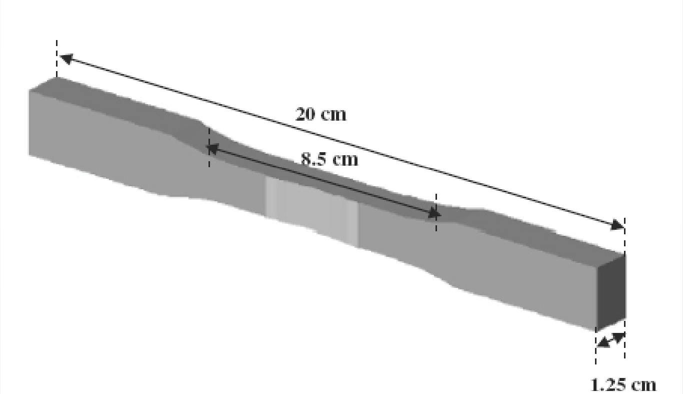
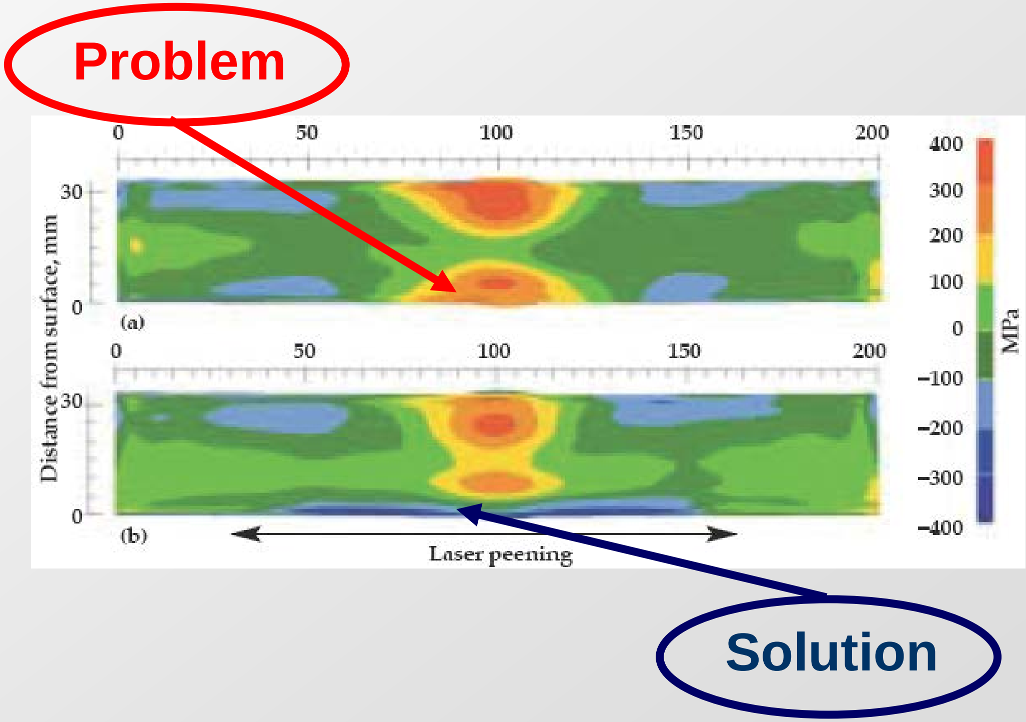


Fig. 4. Dimensions of the tensile specimen.



DISCUSSION AND OUTLOOK

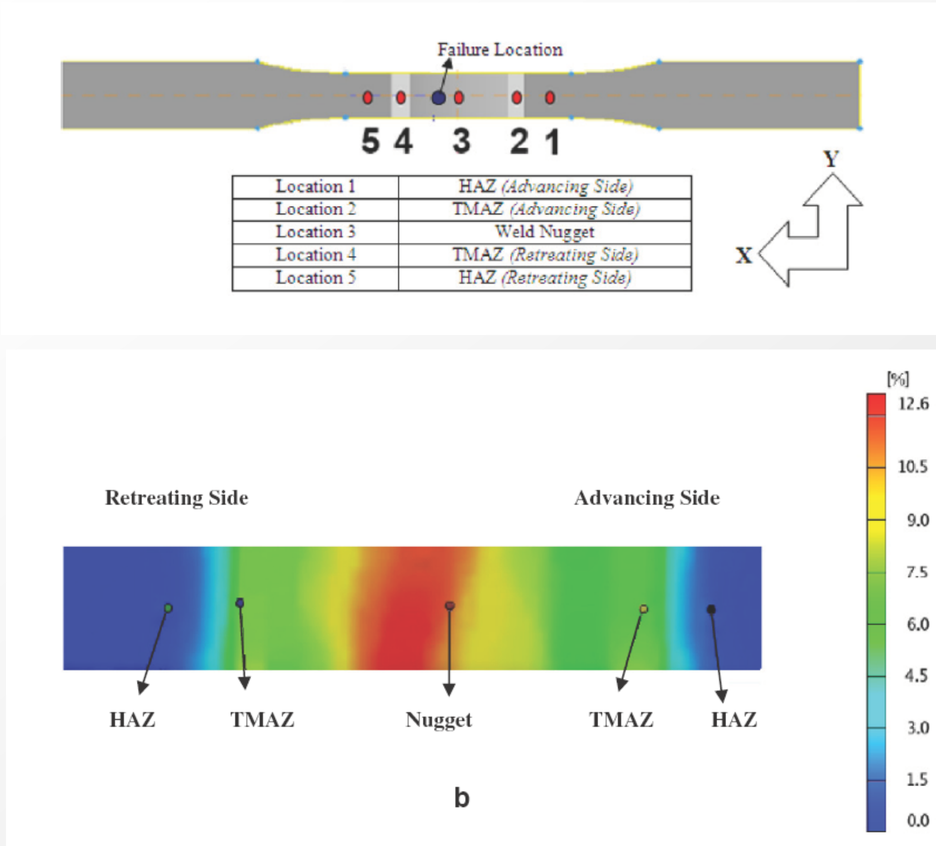


Fig. 10. (a) Tensile properties at different regions of the weld (b) Strain fields in the x-direction for the specimen before failure.

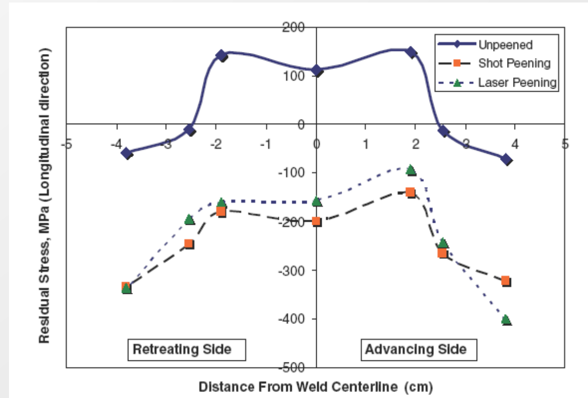


Fig. 11. Residual stresses for the various peened FSW specimens.

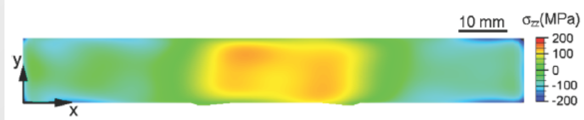


Fig. 12. Two-dimensional map of the measured residual stress for the unpeened FSW specimen.

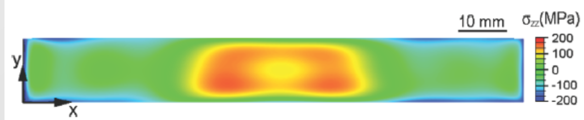


Fig. 13. Two-dimensional map of the measured residual stress for the shot peened FSW specimen.

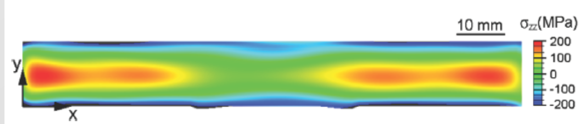


Fig. 14. Two-dimensional map of the measured residual stress for the laser peened FSW specimen.

O. Hatamleh / **International Journal of Fatigue 31 (2009) 974–988**

DISCUSSION AND OUTLOOK

- Important surface resistance and life cycle extension improvements in critical high reliability components by LSP have been experimentally demonstrated. The associate predictive assessment capabilities needed for adequate process design have also been developed and used for theoretical-experimental contrast.
- In view of the important improvements reached in wear behaviour, surface roughness (precursor of improved corrosion resistance) and fatigue life (all of them resulting from the deep compressive residual stresses fields introduced by the process), the LSP technique has to be recognized as a key technology for the enhancement of materials and systems durability and reliability.
- Important technological implementations of LSP in the aerospace, automotive, nuclear and biomedical sectors are under course, anticipating relevant improvements in service reliability and in material preservation and (eco-friendly) efficient use.
- However, despite the availability of the LSP technique at laboratory level, practical developments at industrial level still need to be further accomplished.

ACKNOWLEDGEMENTS

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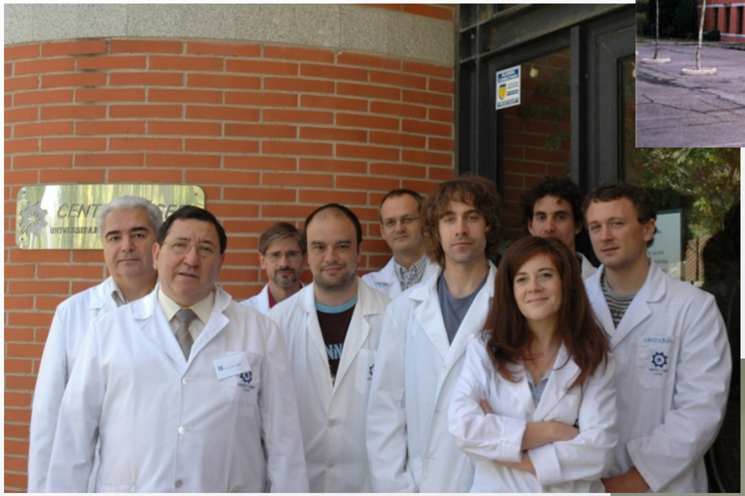
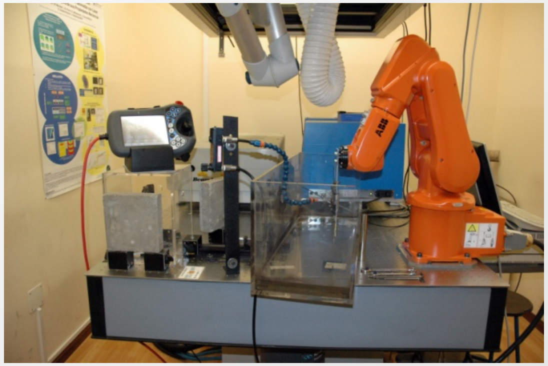
REFERENCES

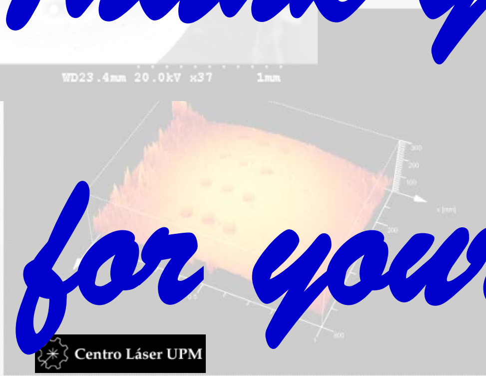
1. Ocaña, J.L. et al.: “A Model for the Coupled Predictive Assessment of Plasma Expansion and Material Compression in Laser Shock Processing Applications”. In: High-Power Laser Ablation II, Claude R. Phipps, Masayuki Niino, Eds., SPIE Proceedings , Vol. 3885, 252–263 (2000)
2. Ocaña, J.L. et al.: “Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser shock processed metallic alloys”. In: High-Power Laser Ablation V, Phipps C.R., Ed.. SPIE Vol. 5548, 642-653 (2004)
3. Ocaña, J.L. et al.: Materials Science Forum, 539-543, 1116-1121 (2007)
4. Morales, M. et al.: Surfaces and Coating Technology, 202 , 2257-2262 (2008)
5. Morales, M. et al.: Applied Surface Science, 255, 5181–5185 (2009)
6. Ocaña, J.L. et al.: “Design Issues of Engineered Residual Stress Fields and Associate Surface Properties Modification by LSP in Al and Ti Alloys”. Proceedings of the Fifth International WLT-Conference on Lasers in Manufacturing 2009. Munich, June 2009. A. Ostendorf et al. Eds.. pp. 387-392 (2009)
7. Ocaña, J.L. et al.: “Laser Shock Processing of Metallic Materials: Coupling of Laser-Plasma Interaction and Material Behaviour Models for the Assessment of Key Process Issues”. In International Symposium on High Power Laser Ablation 2010, C.R. Phipps, Ed. AIP Conference Proceedings, Vol. 1278, pp. 902-913 (2010)
8. Morales, M. et al.: Materials Science Forum, 638-642, 2682-2687 (2010)
9. Morales, M. et al.: International Journal of Structural Integrity, 2, 51-61 (2011)
10. Correa, C. et al.: International Journal of Fatigue, 70, 196–204 (2015)

LSP: An emerging industrial technology

The LSP Team at UPM Laser Centre







Thank you very much for your attention !

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EXPERIMENTAL RESULTS

Material:	Al2024 T3
Pulses:	∅=1,5 mm; τ=10 ns; f=10 Hz; E=1 J/pulse; I=1,41 GW/cm^2
Swept Area :	15x15 mm^2; 2500 pulses/cm^2